# Effective Inspired Oxygen Concentration Measured Via Transtracheal and Oral Gas Analysis

Gerald H Markovitz MD, James Colthurst MBBS, Thomas W Storer PhD, and Christopher B Cooper MD

**BACKGROUND: The fraction of inspired oxygen ($F_{IO_2}$) is quoted for different oxygen delivery systems, but variations in inspiratory flow and tidal volume make precise measurement difficult. We developed a reliable method of measuring the effective $F_{IO_2}$ in patients receiving supplemental oxygen. METHODS: Ten subjects with chronic hypoxemia breathed through a mouthpiece with a sampling probe connected to a mass spectrometer. Four of the 10 subjects had transtracheal catheters that allowed direct sampling of tracheal gas. We used oxygen concentrations of 47% and 97%, and flow rates between 1 L/min and 8 L/min. We also compared oxygen delivery via nasal cannula and transtracheal catheter. Effective $F_{IO_2}$ was derived from plots of the fractional concentrations of carbon dioxide versus oxygen. RESULTS: We found excellent correlation between the effective $F_{IO_2}$ values from tracheal and oral sampling ($r = 0.960$, $P < .001$). With 97% oxygen via nasal cannula, effective $F_{IO_2}$ increased by 2.5% per liter of increased flow ($P < .001$); effective $F_{IO_2}$ reached 32.7% at 5 L/min while $P_{aO_2}$ increased by 12 mm Hg per liter of increased flow. In 4 subjects with a transtracheal catheter, effective $F_{IO_2}$ increased 5.0% ($P < .001$) per liter of increased flow, and $P_{aO_2}$ increased by 13 mm Hg per liter of increased flow, whereas in the same 4 subjects using nasal cannula for oxygen delivery, $P_{aO_2}$ increased by only 6 mm Hg per liter of increased flow. CONCLUSIONS: Exhaled gas sampled at the mouth accurately reflected the effective $F_{IO_2}$ in the trachea. In relation to inspired oxygen flow, the effective $F_{IO_2}$ was lower than is conventionally thought. Compared to nasal cannula, transtracheal catheter approximately doubled the effective $F_{IO_2}$ at a given flow rate. Accurate knowledge of $F_{IO_2}$ should aid clinicians in managing patients with acute and chronic lung diseases.** *Key words: oxygen; transtracheal; inspired; oxygen concentration.* [Respir Care 2010;55(4):453–459. © 2010 Daedalus Enterprises]

## Introduction

The efficacy of oxygen therapy depends on the fraction of inspired oxygen ($F_{IO_2}$), which in turn depends on the method of oxygen supply and delivery. Unfortunately, when supplemental oxygen is given via a low-flow system such as nasal cannula, $F_{IO_2}$ cannot be precisely determined because of entrainment of room air. This methodological study addresses the important need to better understand what $F_{IO_2}$ can be achieved with different oxygen delivery systems. Perhaps the ideal method for determining $F_{IO_2}$ would be to sample tracheal air, but this is not easily accomplished. However, we recruited a small group of patients with transtracheal oxygen catheter. We reversed the flow through the transtracheal catheter to sample tracheal gas while the patient received oxygen via nasal cannula. We used this method to validate a novel technique

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whereby we used intra-breath, expired gas analysis to derive the effective $F_{IO_2}$.

Oxygen therapy via transtracheal catheter was first described by Heimlich in 1982.[1] Subsequent publications showed that oxygen delivered via transtracheal catheter decreased the inspired minute volume[2] and the oxygen cost of breathing,[3] increased exercise tolerance,[4] and reduced dyspnea.[4] These findings led investigators to conclude that transtracheal delivery provides a higher oxygen concentration than nasal cannula, although $F_{IO_2}$ was not specifically measured in any of those studies. Development of the transtracheal catheter introduced an alternative means of oxygen delivery and offers access for measurement of effective $F_{IO_2}$. Conventional estimates suggest that for every liter-per-minute increase in oxygen flow via nasal cannula, effective $F_{IO_2}$ increases by approximately 4 percentage points (eg, supplemental oxygen at 1 L/min raises $F_{IO_2}$ to approximately 24%, 2 L/min raises it to 28%, and up to 6 L/min raises it to 44%).[5] We developed a novel and reliable clinical method of measuring effective $F_{IO_2}$, which could be used to assess the efficiency of oxygen supply and delivery systems. This approach has established, for the first time, parameters for accurately measuring effective $F_{IO_2}$ in patients.

## Methods

### Patients

Ten subjects with chronic hypoxemia, including 4 with transtracheal catheter, were recruited into the study. There were 7 men and 3 women. Eight subjects had obstructive lung disease, one had restrictive lung disease, and one had obesity hypoventilation syndrome. The mean ± SD duration of lung disease was 10.7 ± 6.8 y, and the duration of oxygen therapy was 6.6 ± 2.8 y. The group's mean prescribed oxygen flow rate was 2.9 ± 1.3 L/min (range 1.5–4.0 L/min), and the subjects used their oxygen for a mean 21.8 ± 6.6 h/d.

Written consent was obtained from all participants. The study protocol and informed-consent procedure were approved by the local institutional review board. The study was designed by author CBC and conducted at the University of California, Los Angeles. The oxygen-sieve technology was provided by Oxycare (Slough, England), which funded the research but was not involved in the data collection or analysis.

### Study Protocol

Each subject came to the research laboratory once, for a period of about 4 hours. Two types of apparatus were used to supply oxygen, at predetermined constant flow rates. The output oxygen concentration of the oxygen concentrators was measured via mass spectrometry (MG1100, Perkin Elmer, Wellesley, Massachusetts). One of the oxygen concentrators was a conventional molecular sieve with 2 zeolite columns (492A, Puritan Bennett, Pleasanton, California). The output was tested multiple times, for periods up to 60 min and found to give a consistent output of 97% oxygen. The other oxygen concentrator was a membrane oxygen separator (Oxycare, Slough, England) that drives pressurized air through polymer straws that have different permeabilities to oxygen, nitrogen, and water vapor. The membrane separator gave a consistent oxygen concentration of 47% for at least 60 min.

We compared 2 oxygen-delivery devices: standard nasal cannula and transtracheal catheter. The subjects were seated comfortably at rest, avoiding distractions that might affect their breathing pattern. With all of the subjects, and on 3 occasions, we obtained baseline $F_{IO_2}$ measurements while the subjects breathed room air.

The sequence of combinations of supply and delivery system was randomized with a random-number table. Each time the study conditions were changed, 15 min was allowed for the subject to reach equilibrium. The subjects received oxygen via nasal cannula, from the molecular sieve or from the membrane separator, at various flow rates. The molecular sieve was capable of oxygen flows up to 6 L/min, and we tested 1, 3, and 5 L/min. The membrane separator was capable of oxygen flows up to 10 L/min, and we tested 4, 6, and 8 L/min.

For sampling gas at the mouth we used a standard rubber mouthpiece with a sampling line to the mass spectrometer. With every combination of apparatus and flow rate, gas was continuously sampled, at 100 mL/min, during 10 successive breathing cycles. Gas from the transtracheal catheter was sampled and analyzed in the same manner. The mass spectrometer displayed and stored instantaneous fractional concentrations of carbon dioxide ($F_{CO_2}$) and oxygen ($F_{O_2}$). The analog signals were digitized and plotted as $F_{CO_2}$ versus $F_{O_2}$, as described by Rahn and Fenn.[6] For each condition of measurement, effective $F_{IO_2}$ was obtained as the intercept of the $F_{CO_2}-F_{O_2}$ relationship with the x-axis, ie, when $F_{CO_2}$ was 0%.

After a normal modified Allen test, each patient had an arterial line placed in a radial artery. Arterial blood gases were initially measured while the subject breathed room air, and then again toward the end of each set of measurements under different conditions of oxygen supply and delivery.

### Statistical Analysis

Analyses were performed with statistics software (SPSS, SPSS, Chicago, Illinois). The subjects' demographics and characteristics are expressed as mean ± SD. Measured values of $F_{O_2}$, $F_{CO_2}$ and $P_{aO_2}$ were expressed and compared as mean ± SEM. The Pearson correlation coefficient was

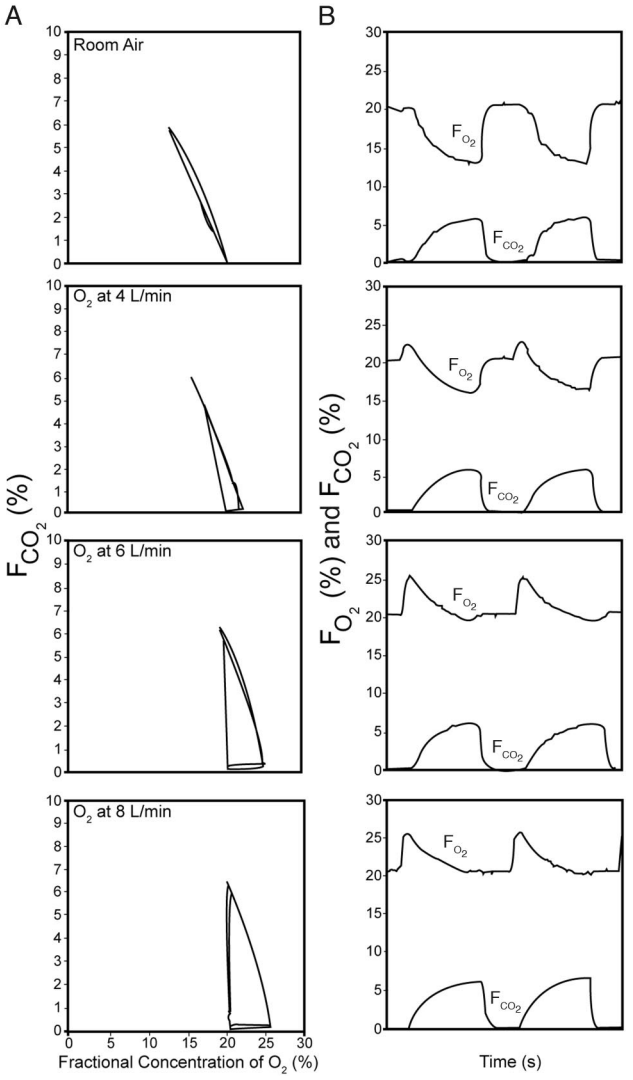


Fig. 1. Raw data from gas sampling at the mouthpiece during quiet breathing (nasal cannula). Left column (A): fractional concentration of carbon dioxide plotted against fractional concentration of oxygen without supplemental oxygen (room air) and with supplemental oxygen (47%) at 4, 6, and 8 L/min. Right column (B): Examples of $F_{O_2}$ and $F_{CO_2}$ in real time from a patient breathing room air, and while breathing supplemental oxygen (47%) at 4, 6, and 8 L/min.

derived to compare effective $F_{IO_2}$ measured at the mouthpiece to that measured in the trachea. We used a mixed-effects model with unstructured covariance matrix to compare effective $F_{IO_2}$ and $P_{aO_2}$ with the different oxygen supply concentrations and delivery methods over the range of flow rates. $P$ values $< .05$ were considered significant.

## Results

### Determination of Effective $F_{IO_2}$

The raw $F_{O_2}$ and $F_{CO_2}$ data were displayed breath-by-breath (Fig. 1A). We plotted $F_{CO_2}$ against $F_{O_2}$ for each of the measurement conditions (molecular sieve vs membrane separator, and nasal cannula vs transtracheal catheter), with the graphical approach first described by Rahn and Fenn.[6] Figure 1B shows examples of data from a patient while breathing room air, and while receiving 47% oxygen from the molecular sieve at 4 L/min, 6 L/min, and 8 L/min.

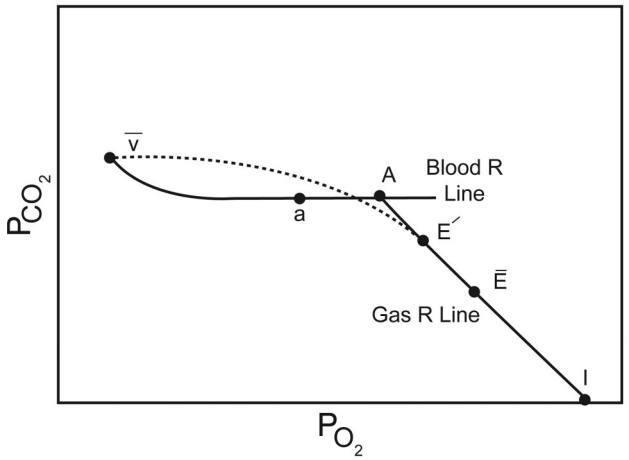


Fig. 2. The $O_2-CO_2$ diagram of Rahn and Fenn.[6] To find the effective fraction of inspired oxygen (effective $F_{IO_2}$) we extrapolate along the gas line to the intersection on the X axis and convert $P_{IO_2}$ (partial pressure of inspired oxygen) to $F_{IO_2}$. I = inspired point. E′ = end-expired point. $\bar{E}$ = mixed expired point. A = alveolar point. a = arterial point. $\bar{v}$ = mixed venous point.

Just as is recognized for breathing room air, the inspired point illustrated in Figure 2 represents the inspired gas concentrations from which effective $F_{IO_2}$ can be determined. This phenomenon is true not only for room air, but also for various conditions of oxygen supply and delivery. Thus, by extrapolating the linear relationship between $F_{CO_2}$ and $F_{O_2}$ to the X axis we can derive the effective $F_{IO_2}$.

### Measured Values of Effective $F_{IO_2}$

Table 1 shows the effective $F_{IO_2}$ data. The baseline room-air $F_{IO_2}$ measurements were highly reproducible in all the subjects. The mean values ± SEM on the 3 occasions of measuring the $F_{IO_2}$ on room were 20.8 ± 0.1%, 20.7 ± 0.1%, and 20.7 ± 0.1%, which is consistent with the expected room-air oxygen concentration.

At the highest studied flow (8 L/min) with the 47% oxygen via nasal cannula, the effective $F_{IO_2}$ was 27.9 ± 0.6% at the mouthpiece and 28.2 ± 0.4% in the trachea.

During transtracheal catheter oxygen delivery, at all flow rates, the effective $F_{IO_2}$ values were significantly higher than those via nasal cannula. With the 97% oxygen supply at 5 L/min, via nasal cannula, the effective $F_{IO_2}$ was

Table 1. Effective $F_{IO_2}$*

| Delivery Method | Sampling Location | Room Air | 97% $O_2$ | | | 47% $O_2$ | | |
|---|---|---|---|---|---|---|---|---|
| | | | at 1 L/min | at 3 L/min | at 5 L/min | at 4 L/min | at 6 L/min | at 8 L/min |
| Nasal cannula | Mouthpiece | 20.8 ± 0.1 | 22.6 ± 0.2 | 27.1 ± 0.7 | 32.7 ± 1.2 | 23.6 ± 0.3 | 25.6 ± 0.5 | 27.9 ± 0.6 |
| | Trachea | 20.7 ± 0.1 | 22.8 ± 0.1 | 27.6 ± 0.5 | 31.8 ± 0.5 | 23.6 ± 0.2 | 25.9 ± 0.5 | 28.2 ± 0.4 |
| Transtracheal catheter | Mouthpiece | 20.7 ± 0.1 | 25.0 ± 0.5† | 34.9 ± 1.4† | 45.2 ± 1.4† | 26.1 ± 0.9† | 29.9 ± 1.5† | 32.0 ± 2.0† |

* Mean ± SEM fraction of inspired oxygen ($F_{IO_2}$) values for 10 consecutive breath cycles.
† $P < .001$ for transtracheal catheter versus nasal cannula, via mixed-effects model.

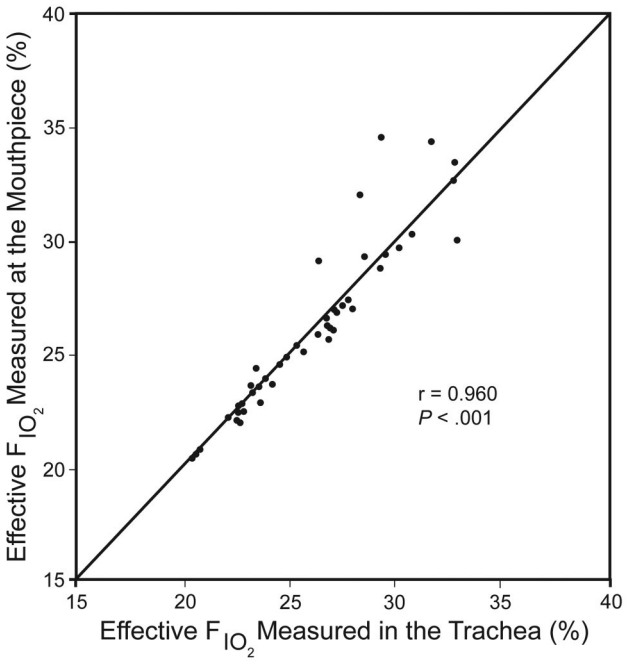


Fig. 3. Effective fraction of inspired oxygen (effective $F_{IO_2}$) measured at the mouthpiece versus in the trachea. There was excellent correlation, based on 59 paired measurements (r = 0.960, $P < .001$).

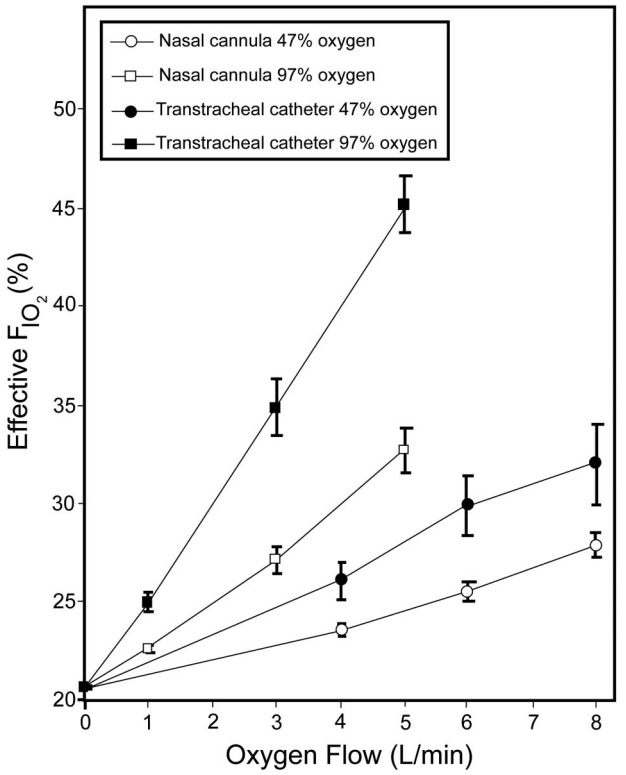


Fig. 4. Effective fraction of inspired oxygen (effective $F_{IO_2}$) versus oxygen flow rate with 2 different oxygen supply systems (membrane separator and molecular sieve) and 2 different oxygen delivery systems (nasal cannula and transtracheal catheter). Data are expressed as mean ± SEM.

32.7 ± 1.2% at the mouthpiece and 31.8 ± 0.5% in the trachea.

With transtracheal catheter delivery and the 47% oxygen supply, at 8 L/min the effective $F_{IO_2}$ was 32.0 ± 2.0%, compared to 45.2 ± 1.4% with the 47% oxygen supply at 5 L/min.

Regardless of the oxygen concentration and delivery system, transtracheal delivery consistently gave higher effective $F_{IO_2}$, at all settings ($P < .001$).

### Comparison of Effective $F_{IO_2}$ With Oral Versus Tracheal Sampling

Figure 3 shows the measured oxygen concentrations at the mouthpiece versus in the trachea. The measurements correlate remarkably well overall (r = 0.960, $P < .001$), although the correlation is less robust at higher oxygen concentrations.

### Comparison of Effective $F_{IO_2}$ Related to Apparatus and Flow Rate

Figure 4 shows the effective $F_{IO_2}$ values, measured at the mouthpiece, plotted against the various flow rates. Transtracheal catheter always delivered higher effective $F_{IO_2}$ than nasal cannula at equivalent flow rates ($P < .001$). We used a mixed effects model to study the change in effec-

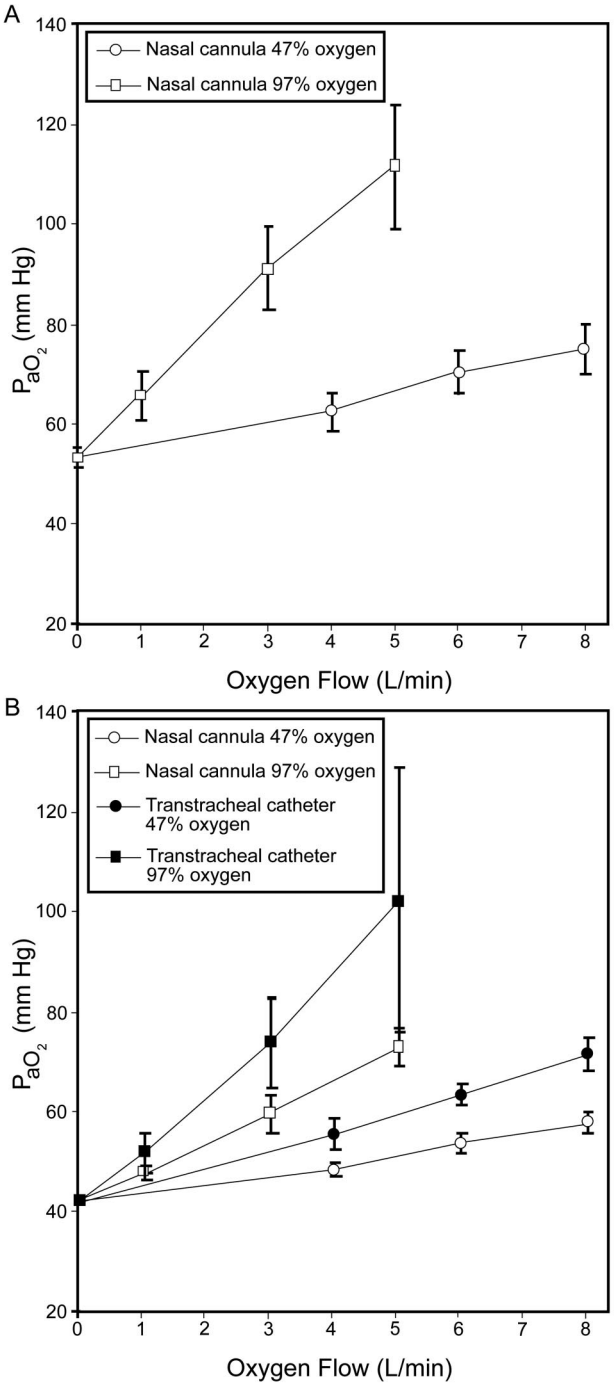


Fig. 5. $P_{aO_2}$ versus oxygen flow. A: Data from all 10 subjects while receiving oxygen only via nasal cannula. B: Data from the 4 subjects who had transtracheal catheter, while they received oxygen only via nasal cannula, and while they received oxygen only via transtracheal catheter. Data are expressed as mean ± SEM.

tive $F_{IO_2}$ in relation to oxygen flow rate. With the 97% oxygen, each liter-per-minute increase in flow via nasal cannula increased effective $F_{IO_2}$ by 2.5% ($P < .001$), compared to 5.0% via transtracheal catheter ($P < .001$).

### Changes in $P_{aO_2}$ With Different Oxygen Supply and Delivery Systems

Figure 5A plots $P_{aO_2}$ versus oxygen flow rate for all the subjects, while they received oxygen via nasal cannula. With 97% oxygen via nasal cannula, $P_{aO_2}$ increased 12 mm Hg per liter increase in oxygen flow ($r^2 = 0.997$; $P < .001$). The $P_{aO_2}$ increases with 47% oxygen were, predictably, less. Figure 5B plots $P_{aO_2}$ versus oxygen flow rate in only the patients with transtracheal catheter, while they received oxygen only via nasal cannula, and while they received oxygen only via transtracheal catheter. With 97% oxygen via transtracheal catheter $P_{aO_2}$ increased 13 mm Hg per liter increase in oxygen flow ($r^2 = 0.993$; $P = .052$), whereas in the same 4 subjects with nasal cannula oxygen delivery, $P_{aO_2}$ increased by only 6 mm Hg per liter increased oxygen flow ($r^2 = 0.998$).

## Discussion

We have described and validated a novel and simple method for deriving the effective $F_{IO_2}$. With this method, sampling gas at the mouthpiece or in the trachea gave comparable effective $F_{IO_2}$ values. In addition we have shown that the effective $F_{IO_2}$ with supplemental oxygen via nasal cannula is lower than is conventionally thought, and that transtracheal delivery provides significantly higher effective $F_{IO_2}$ than standard nasal cannula delivery, at equivalent flow rates.

Non-rebreather low-flow oxygen systems do not allow precise determination of $F_{IO_2}$, because $F_{IO_2}$ depends on the oxygen reservoir, the oxygen flow, and the patient's ventilatory pattern. Several sources quote the expected $F_{IO_2}$ increase to be 4% per liter-per-minute flow increase via nasal cannula.[5,7-9] For example, one textbook calculated that, with nasal cannula, at 6 L/min (or 100 mL/s), the anatomical reservoir would provide 50 mL of 100% oxygen, the cannula would supply 100 mL of 100% oxygen, and the remaining 350 mL of a 500-mL tidal volume contains 70 mL of oxygen (at room air 20%),[5] so:

$$F_{IO_2} = (50\ mL\ O_2 + 100\ mL\ O_2 + 70\ mL\ O_2)/500\ mL\ gas = 44\%$$

With a flow rate of 5 L/min the calculated $F_{IO_2}$ is said to be 40%. By contrast, we found that 5 L/min of 97% oxygen via nasal cannula provided an $F_{IO_2}$ of only 32.7 ± 1.2% (via sampling at the mouthpiece) or 31.8 ± 0.5% (via sampling in the trachea).

We have shown that providing an effective $F_{IO_2}$ as high as 40% requires transtracheal delivery. For instance, our subjects had $F_{IO_2}$ of 45.2 ± 1.4% with 5 L/min of 97% oxygen via transtracheal catheter. Figure 3 and Table 1

confirm that transtracheal oxygen provides consistently higher effective $F_{IO_2}$ than can be achieved via nasal cannula.

Four of our patients had indwelling transtracheal catheters. Although this is a small subgroup, we took numerous samples of transtracheal and exhaled gas. We have shown rather convincingly that our method for determining effective $F_{IO_2}$ applies just as well to both gas-sampling locations. Furthermore, exhaled gas accurately represents the tracheal $F_{IO_2}$ with different oxygen supply concentrations and at various flow rates. To our knowledge, this is the first systematic validation that gas sampled at the mouthpiece accurately represents the tracheal concentration. In healthy subjects with a percutaneously placed tracheal sensing catheter, Gibson et al found the highest absolute inspired tracheal oxygen concentration to be 23.6% at 3 L/min, and 25.4% at 5 L/min, with nasal cannula.[10] In another report, in patients with permanent tracheostomies the tracheal oxygen concentration was 25% at 3 L/min.[11] Our findings concur reasonably well with those data, but contrast with a published formula that would predict the $F_{IO_2}$ to be 32% at 3 L/min and 40% at 5 L/min.[9]

We further evaluated the efficacy of the different oxygen supply and delivery systems in this study with arterial blood gas analysis. For the group as a whole, the 97% oxygen via nasal cannula increased $P_{aO_2}$ 12 mm Hg per liter increase in oxygen flow. This finding should be a useful guide for prescribing oxygen therapy, since it allows an estimate of the achievable $P_{aO_2}$ for a given oxygen prescription. However, this estimate is only a generalization, and the actual therapeutic response should be separately validated in each individual patient. With 97% oxygen, transtracheal catheter delivery increased $P_{aO_2}$ by 13 mm Hg per liter increase in oxygen flow. Note, however, that the transtracheal-catheter patients had more severe baseline hypoxemia ($P_{aO_2}$ 42 mm Hg while breathing room air, compared to 53 mm Hg for the whole group). Also, their observed increase in $P_{aO_2}$ in response to nasal cannula oxygen delivery was only 6 mm Hg per liter of increased oxygen flow. Overall, transtracheal catheter gave higher effective $F_{IO_2}$ and $P_{aO_2}$ than nasal cannula, regardless of the supplied oxygen concentration. These findings illustrate the advantages of transtracheal oxygen, particularly for patients with refractory hypoxemia.

The transtracheal catheter was developed in the early 1980s, as an alternative to nasal cannula oxygen.[12-14] More recent surgical techniques have simplified the procedure.[15,16] Many benefits of transtracheal catheter oxygen have been described. For example, in patients with refractory hypoxemia, transtracheal oxygen reduces bulk oxygen use by 29.4%[17] and reduces the oxygen flow requirement by 47–58% at rest[18,19] and by 30% during exercise.[18] These oxygen savings should extend the use of portable oxygen devices by ambulatory patients, and thereby facilitate greater independence. In addition, patients on transtracheal catheter oxygen have improved oxygenation from the reduced oxygen cost of breathing[3] because of the reduced inspired minute volume and inspiratory work of breathing,[2] which may reduce the energy expenditure from breathing.[2] Other published benefits include reduced hematocrit,[12] increased exercise tolerance,[4,20] and improved arterial oxygenation during sleep.[21] Transtracheal oxygen has even been suggested as an alternative to other therapies for patients with refractory obstructive sleep apnea.[22,23] Our study implies that these benefits derive from the substantially higher effective $F_{IO_2}$ values with transtracheal oxygen, compared to nasal cannula.

### Limitations

First, we studied patients with severe lung disease, so our results may not be generalizable to other populations. Also, the group with transtracheal catheter had more severe disease than the group as a whole. For example, the mean $P_{aO_2}$ while breathing room air was 42 ± 4 mm Hg in the transtracheal catheter subjects, compared to 54 ± 11 mm Hg in the whole group. However, our main purpose was to test the reliability of our method for determining effective $F_{IO_2}$, not to compare the 2 subject subgroups.

Second, we did not measure respiratory rate or tidal volume, and these could certainly influence room-air entrainment in patients using low-flow oxygen systems. Nevertheless, every derivation of effective $F_{IO_2}$ was made over 10 breath cycles (ie, at least 30 s), and we would expect that sampling interval to limit the variability of the measurements related to alterations in breathing pattern.

Third, we studied only 10 subjects, but we believe our data are more robust than might be suggested by that small number, because the 4 patients with transtracheal catheter provided 59 paired comparisons of effective $F_{IO_2}$ measured at the mouthpiece and in the trachea, and the correlation we report (see Fig. 3) is based on those data.

This is a small methodological study that builds on classic work, such as the study by Mithoefer et al,[24] who set out to predict the $P_{aO_2}$ response to supplemental oxygen from basic principles, and the study by Bengtsson et al,[25] who used end-tidal oxygen tension as an estimate of alveolar oxygen tension. We believe our approach has practical advantages over those other methods, in that we actually derive the effective $F_{IO_2}$.

The fact that transtracheal oxygen therapy is not widely used at present might limit interest in our findings. On the other hand, this clear demonstration of the superiority of transtracheal delivery might revive interest in this interesting therapeutic technique.

## Conclusions

We have validated a novel technique for determining effective $F_{IO_2}$ under different conditions of oxygen supply and delivery. We used intra-breath analysis of expired gas concentrations, which are not influenced by variations in breathing pattern. The derived $F_{IO_2}$ values at various oxygen flow rates via nasal cannula showed that $F_{IO_2}$ is substantially less than has been suggested in textbooks and journals. We also investigated a developing technology for oxygen supply, the membrane separator, which might someday provide an alternative to the molecular sieve for concentrating oxygen from room air. We confirmed that transtracheal oxygen delivery is substantially more efficient than nasal cannula delivery, and transtracheal delivery approximately halves the oxygen flow requirement to achieve a given $F_{IO_2}$. Our findings pave the way for further investigation of effective $F_{IO_2}$ under other conditions, such as exercise or sleep.

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### REFERENCES

1. Heimlich HJ. Respiratory rehabilitation with transtracheal oxygen system. Ann Otol Rhinol Laryngol 1982;91(6 Pt 1):643-647.
2. Couser JI Jr, Make BJ. Transtracheal oxygen decreases inspired minute ventilation. Am Rev Respir Dis 1989;139(3):627-631.
3. Benditt J, Pollock M, Roa J, Celli B. Transtracheal delivery of gas decreases the oxygen cost of breathing. Am Rev Respir Dis 1993; 147(5):1207-1210.
4. Dewan NA, Bell CW. Effect of low flow and high flow oxygen delivery on exercise tolerance and sensation of dyspnea: a study comparing the transtracheal catheter and nasal prongs. Chest 1994; 105(4):1061-1065.
5. Shapiro BA, Harrison RA, Walton JR. Clinical application of blood gases, 3rd edition. Chicago: Year Book Medical; 1982.
6. Rahn H, Fenn WO. A graphical analysis of the respiratory gas exchange: the $O_2$-$CO_2$ diagram. Washington DC: American Physiological Society; 1955.
7. Hoffman LA. Novel strategies for delivering oxygen: reservoir cannula, demand flow, and transtracheal oxygen administration. Respir Care 1994;39(4):363-377.
8. Stewart AG, Howard P. Devices for low flow $O_2$ administration. Eur Respir J 1990;3(7):812-817.
9. Tiep B. Portable oxygen therapy with oxygen conserving devices and methodologies. Monaldi Arch Chest Dis 1995;50(1):51-57.
10. Gibson RL, Comer PB, Beckham RW, McGraw CP. Actual tracheal oxygen concentrations with commonly used oxygen equipment. Anesthesiology 1976;44(1):71-73.
11. Schacter EN, Littner MR, Luddy P, Beck GJ. Monitoring of oxygen delivery systems in clinical practice. Crit Care Med 1980;8(7):405-409.
12. Heimlich HJ, Carr GC. The micro-trach: a seven-year experience with transtracheal oxygen therapy. Chest 1989;95(5):1008-1012.
13. Timms RM, Kvale PA, Anthonisen NR, Boylen CT, Cugell DW, Petty TL, Williams GW. Selection of patients with chronic obstructive pulmonary disease for long-term oxygen therapy. JAMA 1981; 245(24):2514-2515.
14. Christopher KL, Spofford BT, Brannin PK, Petty TL. Transtracheal oxygen therapy for refractory hypoxemia. JAMA 1986;256(4):494-497.
15. Lipkin AF, Christopher KL, Diehl S, Yaeger ES, Jorgenson S. Otolaryngologist's role in transtracheal oxygen therapy: the minitrach procedure. Otolaryngol Head Neck Surg 1996;115(5):447-453.
16. Christopher KL. Transtracheal oxygen catheters. Clin Chest Med 2003;24(3):489-510.
17. Yaeger ES, Goodman S, Hoddes E, Christopher KL. Oxygen therapy using pulse and continuous flow with a transtracheal catheter and a nasal cannula. Chest 1994;106(3):854-860.
18. Christopher KL, Spofford BT, Petrun MD, McCarty DC, Goodman JR, Petty TL. A program for transtracheal oxygen delivery: assessment of safety and efficacy. Ann Intern Med 1987;107(6):802-808.
19. Kampelmacher MJ, Deenstra M, van Kesteren RG, Melissant CF, Douze JM, Lammers JW. Transtracheal oxygen therapy: an effective and safe alternative to nasal oxygen administration. Eur Respir J 1997;10(4):828-833.
20. Wesmiller SW, Hoffman LA, Sciurba FC, Ferson PF, Johnson JT, Dauber JH. Exercise tolerance during nasal cannula and transtracheal oxygen delivery. Am Rev Respir Dis 1990;141(3):789-791.
21. Chauncey JB, Aldrich MS. Preliminary findings in the treatment of obstructive sleep apnea with transtracheal oxygen. Sleep 1990;13(2): 167-174.
22. Farney RJ, Walker JM, Elmer JC, Viscomi VA, Ord RJ. Transtracheal oxygen, nasal CPAP and nasal oxygen in five patients with obstructive sleep apnea. Chest 1992;101(5):1228-1235.
23. Series F, Forge JL, Lampron N, Cormier Y. Transtracheal air in the treatment of obstructive sleep apnoea hypopnoea syndrome. Thorax 2000;55(1):86-87.
24. Mithoefer JC, Keighley JF, Karetzky MS. Response of the arterial $PO_2$ to oxygen administration in chronic pulmonary disease: interpretation of findings in a study of 46 patients and 14 normal subjects. Ann Intern Med 1971;74(3):328-335.
25. Bengtsson J, Bake B, Johansson A, Bengtson JP. End-tidal to arterial oxygen tension difference as an oxygenation index. Acta Anaesthesiol Scand 2001;45(3):357-363.